Appendix XV

Summary of Other Types of Ecological Effects

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Contents

1. Introduction

The citizens of California value the state's natural ecosystems for their intrinsic qualities, as well as for the goods and services they provide. The more tangible benefits that humans derive from natural ecosystems are marketable products, such as timber, fish, forage, and pharmaceuticals, along with diverse recreational opportunities. Natural ecosystems are the principal reservoir for sustaining biodiversity, and there is extensive literature on the reasons for preserving biodiversity (Ehrlich and Ehrlich, 1992). Many people obtain enjoyment and satisfaction from experiencing nature or from simply knowing that relatively pristine ecosystems exist and will be available for future generations. Finally, and perhaps most important, ecosystems — through their normal functioning — supply many life support services for the planet and help maintain local environmental quality. Examples include air and water purification, erosion control, oxygen replenishment, carbon dioxide absorption, regional climate regulation, and pest and pathogen control.

The reports by Lenihan et al. (Appendix IV) and Galbraith et al. (Appendix V), introduce some of the potential effects of climate change on terrestrial ecosystems in California and how climate change will interact with ongoing urbanization to affect the distribution of vegetation and biodiversity. However, because of the relatively primitive state of ecological modeling relative to the complexity of ecosystems, available models, including MC1, do not consider all the types of ecological effects that may be of interest. For example, they do not simulate the effects of climate change on animal species or the effects that animals have on vegetation properties or ecosystem functioning. In addition, the two reports do not consider how freshwater and coastal marine ecosystems might be affected by climate change. This appendix briefly summarizes other possible effects of climate change on the California's ecosystems, and is based heavily on the report by Field et al. (1999).

Before discussing the diverse and complex effects that may be observed throughout the next century, it is important to recognize that climate change will be imposed on ecosystems that are already experiencing a variety of stresses and changes. In some cases, other threats to the integrity of specific ecosystems or species may be so serious that the additional stresses from climate change will not be noticeable or will not make a large difference. In most cases, however, interactions with other stresses are likely to exacerbate the effects of climate change.

The report by Galbraith et al. considered how climate change and urbanization together could affect the distribution of ecosystems in the state. However, a reduction in the amount of area occupied by different vegetation types (i.e., habitat loss) as a result of converting land to an urban state is only one of the consequences of urbanization. Loss of habitat has two other related effects. First, as the total area inhabited by any particular vegetation type or species gets reduced, the population sizes of the resident native species almost always must decrease accordingly. It is a well-established biogeographic principle (Brown and Lomolino, 1998) that smaller populations are more likely to go extinct. Loss of habitat, then, is almost invariably accompanied by the extinction of species. Among the first species to go extinct will be rare, local endemics, as well as species that have large area requirements (e.g., large carnivores).

Second, an important correlate of urbanization is fragmentation. As areas of natural habitat become more and more isolated (i.e., islands) within a landscape dominated by humans, migration between suitable habitat patches becomes more problematic. This is particularly important in the context of climate change because, as the climate changes, species will need to migrate, potentially tens to hundreds of miles, to remain in climatically suitable habitats. The combined effects of habitat loss and fragmentation represent the greatest threats to California biodiversity.

Another critically important stress that could interact with climate change is the continued introduction of invasive species. Both terrestrial and aquatic ecosystems of California have already been significantly altered by invasive species. For instance, non-native annual grasses have replaced native perennial grasses throughout most of California's grasslands, woodlands, and arid lands, resulting in changes that have important implications for grazing, fire regimes, and erosion control. In addition to grasses, a wide variety of other plants — from noxious weeds to trees — have invaded and modified natural ecosystems. Invasive animals also pose important threats. Exotic pathogens and insect pests, such as gypsy moth, are threatening many native plant species. Freshwater and estuarine ecosystems seem to be particularly susceptible. A large proportion of the freshwater fish species in California are exotic, and San Francisco Bay may be the most invaded estuarine system in the world (Cohen and Carlton, 1998). Invasive species are of particular concern in the context of climate change because they are, by definition, very aggressive and mobile. This means that at a time when climate change is, effectively, disturbing even pristine ecosystems and causing species to have to migrate to new locations, invasive species may be able to invade such locations first and prevent or delay the successful establishment of the desirable native species.

Still other stresses and changes that could interact with climate change come in the form of air and water pollution, and the diversion of fresh waters to meet human needs. Most of California's freshwater and terrestrial ecosystems are not as polluted as those in many parts of the United States, but it will be a challenge to avoid further impacts in the face of a growing population. Pollution is a concern because animals or plants already under stress from a pollutant may be less able to tolerate or adjust to a changing climate. California's freshwater ecosystems, especially those in the southern and central parts of the state, have already been dramatically altered by the diversion of water for irrigation and other human uses. Unless levels of precipitation increase significantly, climate change is likely to make water an even rarer and more valuable commodity, which will make protecting freshwater ecosystems even more difficult.

2. Terrestrial Ecosystems

Climate change is likely to affect California's natural ecosystems in three fundamental ways. First, it may change the geographic distributions of vegetation or ecosystem types. Second, it can affect the functioning of ecosystems and the goods and services they provide. Finally, it can change the distributions and abundance of individual species, which means that interactions among species and overall biodiversity may be affected. The Lenihan et al. work is a state-of-the-art analysis of the first type of effect, subject to the limitations already discussed, and it also covers some aspects of ecosystem functioning, including carbon storage and fire regimes. The rest of this appendix will focus on other ecosystem processes and on effects on individual plant and animal species.

One of the most important and widely used indicators of ecosystem functioning and health is the net primary productivity, or the total amount of plant growth per year in a particular ecosystem or region. Because all organisms in an ecosystem ultimately depend on plants for their food or energy, a change in productivity is likely to have fundamental effects on an ecosystem. Changes in productivity also have direct implications for humans, because the amount of timber produced in forests and the amount of forage in grasslands are directly related to the productivity of those ecosystems. The productivity of an ecosystem depends heavily on climatic conditions, as well as the concentration of carbon dioxide (CO_2) in the atmosphere, so changes in climate will almost always alter productivity.

How productivity will change for different California ecosystems will be a function of the timing and magnitude of changes in temperature and precipitation, as well as CO_2 concentration. Timing is important because of California's highly seasonal climate, particularly in terms of precipitation. Productivity in many terrestrial ecosystems in California is water-limited, so changes in precipitation patterns, which are least predictable, will be especially crucial in determining how productivity changes. If increases in precipitation are insufficient to offset increased temperatures and evaporation, the summer drought period could increase in length and severity. Higher levels of CO_2 have a fertilizing effect on plant growth and productivity if other resources (water and nutrients) are available in sufficient quantities, but experiments on natural ecosystems demonstrate that the benefit is often limited (Mooney et al., 1999). Another effect of increasing atmospheric CO_2 concentration is that plants are able to use available water more efficiently (more growth for a given amount of water). Increasing CO_2, then, may compensate in part for decreases in water availability, either as a result of decreases in the amount of precipitation or increases in evaporation resulting from higher temperatures. Increases in temperature are likely to decrease productivity during the hot, dry summer months for any plants active during that period, but plants that grow during the cool, wet winter months could actually benefit from higher temperatures.

Fog, especially during the summer, is an ecologically important feature of California's central and northern coast. A significant proportion of the moisture available to plants in coastal forests (e.g., redwoods) comes from fog drip — water that is deposited on leaves and drips to the forest floor. The appearance and the productivity of redwoods forests depend on this input of moisture. If climate change increases the temperature of coastal waters or reduces the upwelling of cold water, it could significantly reduce the occurrence of coastal fogs. This could alter the productivity, and ultimately the species composition, of coastal ecosystems.

The Lenihan et al. analyses of changes in vegetation distribution and carbon stocks can be used to infer how productivity may change. Simulations of future climate that include significant increases in precipitation (i.e., the Hadley scenario and the T3P18 and T5P30 scenarios) all show forests expanding, which in most cases would involve an increase in productivity. In addition, total vegetation carbon across the entire state increases significantly under these scenarios, and that also reflects an increase in productivity. Under the drier scenarios (the Parallel Climate Model [PCM], the T3P0, and the T5P0), the increase in total vegetation carbon is much less, indicating lesser increases in productivity.

Productivity is generally regarded as a property of ecosystems or of particular vegetation types, and controls on productivity are reasonably well understood. Therefore, it is feasible to make projections about how productivity might change for the limited number of vegetation types that occur in an area (seven, in the case of the MC1 simulations for California). This contrasts with the challenge of attempting to project effects of climate change on biodiversity or of projecting how individual species will respond. Thousands of species comprise California's flora and fauna, and each one is ecologically unique. In relatively few cases do scientists have enough information on the ecological requirements of individual species to be able to reasonably project how they will be affected by climate change. Yet conserving biodiversity is of broad concern, and conservation planners must incorporate climate change into their planning. It also is essential to know whether climate change could represent a significant threat to biodiversity in terms of causing species to become extinct.

Because climate is so important in determining the distributions of plant species, ecologists have used this information to conduct very general analyses of whether climate change could affect plant diversity. This approach assumes that the geographic range of a particular species is defined by current climate conditions. If climate changes and climatic zones shift, we can predict a new geographic range within which the original climatic conditions still exist. To survive climate change, the plant species must exist in or migrate to this new region. Very simple climate change scenarios (temperature increase only) were used to conduct an analysis of this type for the flora of North America north of Mexico (The Nature Conservancy, 1993). In that analysis, a species was considered "vulnerable" to climate change if its projected new range was totally disjunct (separate from) its current range. For a 5°C increase in temperature, 15% to 20% of plant species across the United States would be vulnerable. Not surprisingly, rare species (which usually have narrower geographic distributions) were more vulnerable. Because of its large flora and unique climate compared to surrounding areas, California has a large number of endemic and relatively narrowly distributed plant (and animal) species. Therefore, California is an area where climate change may present challenges for many species.

Species will not become extinct as a result of climate change if they can migrate to and establish in new habitats where the climatic conditions are suitable. The crucial question becomes whether species will be able to migrate fast enough to keep up with climate change (Pitelka et al., 1997). Ecologists do not know enough about plant migration rates, especially for rarer species, to answer this question, but there are reasons for both pessimism and optimism. The development and fragmentation of natural habitats means that species may have fewer options for places to establish and also must be able to cross the “barriers” created by roads, housing developments, and agricultural fields, among others. As noted earlier, exotic species could out-compete migrating native species, preventing them from establishing in new areas. And if the range of a species is also dependent on other ecological factors in addition to climate (e.g., unusual soil conditions), those conditions may not exist where the climate is suitable.

On the positive side, long-lived plant species may be able to persist in their current habitats for many years after climatic conditions change, which means that there is more time for migration to occur. In addition, because of the complexity of California’s geography (including topography), many species actually occur over broad latitudinal ranges but are restricted to particular microhabitats or microclimates within any one area. In many cases species may need to migrate only short distances to find suitable climatic conditions (e.g., upslope a few hundred meters), rather than hundreds of miles in latitude. Finally, in a last bit of optimistic evidence, ecologists are discovering that many species of plants and animals are already beginning to shift their ranges (Walther et al., 2002), offering hope that many species will be able to adjust their ranges quickly enough to survive.

Making a distinction between local and global extinction of species is important. A species is globally extinct if it no longer can be found anywhere in the world. It is locally extinct if it disappears from an area where it existed previously. Although the extent to which climate change will cause global extinctions remains unclear, there is no question that local extinctions will be common as species disappear from one area and migrate to another. This means that conservation measures that were previously established to protect particular species may no longer be suitable for those species under climate change.

Projecting the effects of climate change on particular species becomes even more difficult in cases where the success of one species of interest depends heavily on another. In such situations it is not sufficient to understand the climatic requirements of the species in question. We must also understand the controls on the interaction between the species, as well as the climatic requirements of the second species. Examples include relationships between plants and their pollinators, plants and their dispersal agents, plants and their herbivores, and predators and their prey. Relatively few studies have been conducted on how these interactions will be affected by climate change, but at least one study suggests that plant-pollinator and plant-dispersal agent relationships could be disrupted in regions with Mediterranean-type climates (Bond, 1995).

Species interactions involving pests and pathogens and their hosts are of particular interest in terms of effects of climate change. Pests and pathogens can have dramatic effects on entire ecosystems. They can also have direct economic impacts, as, for example, when insects damage timber trees. Virtually all species have natural enemies, so the sheer number of relationships defies systematic analysis, and generalizations about the effects of climate change are difficult, if not impossible, to make. Those studies that have been done simply illustrate that the effects of climate change vary widely depending on the particular species involved.

The effect of elevated CO_2 on the interactions among plants and their herbivorous insect pests has been somewhat better investigated than other aspects of climate change (Lincoln et al., 1993). It has been widely observed that elevated CO_2 causes plants to have a higher ratio of carbon to nitrogen in their leaves and other tissues, which translates to less protein. Because herbivorous insects require the protein, they may end up eating more plant tissue to satisfy their needs. This could result in greater overall herbivore damage to the host plants. On the other hand, it is generally found that these insects grow more slowly, which directly or indirectly could lead to less damage.

Even though the diversity and complexity of species interactions does make generalization difficult, it is likely that plants under stress from climate change will be more susceptible to attack by certain pests and pathogens. It is well known that forest trees already under stress from one agent will be more susceptible to other stressors (Manion, 1981), and most examples of widespread forest mortality in the West are the result of trees being under stress from drought and then being attacked by bark beetles (Miller, 1989). Extensive areas of tree mortality from bark beetle were observed in the Sierra Nevada after the drought in the late 1980s. If climate change causes major forest trees to experience greater drought stress, bark beetle infestations could become an even more serious problem. The simulations that Lenihan et al. did with MC1 illustrated the complex interactions among climate change, fire, and vegetation. In particular, the presence of fire can dramatically change the type of vegetation that would be expected as a result of the climate conditions alone. The same could be true of major insect pests, but these have not been incorporated into any ecological models of climate change effects.

3. Freshwater Ecosystems

California's freshwater ecosystems could be affected by climate change in many ways. The most obvious and likely effect will be an increase in the mean temperature of the state's lakes, reservoirs, rivers, streams, and marshes. The distributions of most species of freshwater plants and animals are highly dependent on temperature, so a significant increase in temperature is likely to cause changes in the distributions of aquatic organisms that are similar in magnitude to the changes projected for terrestrial vegetation. For instance, fish (such as trout) that require cold water could become less common and restricted to higher elevations or more northerly river systems. Like terrestrial species, aquatic species may need to migrate to entirely new geographic locations to find suitable habitats. Just as habitat fragmentation and development may create barriers to the migration of terrestrial species, so too may dams, reservoirs, and water diversions create barriers for aquatic species.

Temperature is a key factor in controlling metabolic rates of aquatic organisms and the overall productivity of aquatic ecosystems, with warmer systems typically having higher productivities. In areas where nutrient runoff is a problem (e.g., lakes and reservoirs with adjacent agricultural areas), higher temperatures could increase the risk of nuisance algal blooms (Poff et al., 2002). Warmer water also holds less oxygen, so increases in temperature could cause the exclusion of species with high oxygen demands.

The second major consequence of climate change for aquatic ecosystems would be changes in water flow regimes. This could be a particular problem for California, which already has a relatively dry and highly seasonal climate. Many of California's streams and rivers receive most of their water from melting snow. As the climate warms, snowmelt will occur earlier, increasing winter and early spring runoff and decreasing summer runoff. Because flows are already low in the late summer, further reductions could present serious problems for many aquatic organisms. Already, there is evidence that the timing of runoff in the Sierra Nevadas is changing (Aguado et al., 1992; Pupacko, 1993). Changes in river flows could be especially important for already threatened populations of salmon.

Changes in runoff patterns and streamflow would also have impacts on the receiving ecosystems, including lakes, wetlands, and estuaries. For mountain lakes, changes in flow regimes could affect turnover times, length of ice cover, and mixing (Field et al., 1999), all of which are important in controlling biological processes in the lakes. Human activities, including pollution and water diversions, already have a significant impact on the wetlands of the Central Valley. Reductions in summer flows to wetlands could further stress the systems and make them less suitable habitats for migratory birds (Field et al., 1999).

4. Coastal Marine Ecosystems

California's coastal ecosystems include an extensive coastline and intertidal zone that spans a wide latitudinal range, estuaries ranging in size up to the San Francisco Bay, and offshore systems. In spite of the importance of coastal ecosystems as sources of food, recreation, and other goods and services, the potential effects of climate change on marine ecosystems have not been investigated in as much detail as have effects on terrestrial ecosystems. It is much more difficult to do ecosystem-level experiments on most marine systems, and a comparable history of ecosystem model development to provide models that could be readily applied to the climate change issue is lacking. However, a basic understanding of marine systems, combined with some recent observational studies, suggests that these systems will be sensitive to climate change (Francis, 1990; Beardall et al., 1998; Field et al., 1999).

Climate change could affect marine ecosystems through a variety of direct and indirect pathways (Kennedy, 1990; Beardall et al., 1998). An increase in water temperature is one of the most obvious and likely effects. In addition, however, we must consider possible effects of changes in sea level, currents, freshwater inflows, and salinity.

Evidence that changes in water temperature affect marine organisms already exists. A recent study in California took advantage of a careful survey of intertidal invertebrates done in the early 1930s to evaluate how an increase in sea water temperature over the period from the 1930s to 1993 and 1994 affected the distribution of species (Barry et al., 1995; Sagarin et al., 1999). The investigators found that the abundances of a number of southern species had increased, and that those of most northern species had declined. A larger scale analysis of how changes in sea surface temperature and associated events (e.g., El Niños) affect marine ecosystems in the northeast Pacific Ocean also concluded that effects on distribution ranges and abundances of marine organisms can be significant (McGowan et al., 1998). It is important to recognize that even small changes in temperature can have dramatic effects on natural communities if the changes affect critical species whose ecosystem-level effects are disproportionate to their size or abundance. Sanford (1999) has documented this for a species of starfish on the coast of Oregon.

A topic of growing interest and urgency in recent years is the apparent increase in outbreaks of marine diseases, with numerous incidents of mass mortality of a wide range of marine organisms including plants, invertebrates, and vertebrates (Harvell et al., 1999). This concern extends to diseases that affect humans and are carried by marine organisms. To some extent the increase in reports may be the result of improved reporting and detection, but there is also strong evidence to indicate that climate change has a role, as do other stresses such as pollution, habitat destruction, and human transport of marine species to new environments. For instance, there are numerous cases where disease outbreaks are related to El Niño events or where changes in the ranges of pathogens are related to climate fluctuations. Overall, it appears that global warming, combined with human activities that facilitate the spread of pathogens, is creating new opportunities for these organisms to affect new species or populations.

Estuaries are critical coastal ecosystems from economic, recreational, and ecological perspectives, and the San Francisco Bay is one of the largest estuaries in the United States. Estuaries, which are among the most productive ecosystems on earth, support many important fisheries. They are used extensively for recreational purposes, provide habitat for many marine birds species, and supply valuable ecosystem services. Because they are shallow and depend on both fresh water and sea water supplies, they are potentially sensitive to a variety of stresses associated with climate change (Kennedy, 1990). Different plant and animal species are adapted to different points on the fresh to salt water gradient that exists in estuaries. If climate change alters the amount of fresh water that flows into an estuary or alters the circulation patterns, it could dramatically affect the distributions and abundances of estuarine species. Sea level rise represents a particularly serious threat to estuaries because they are so shallow; a small change in sea level could flood extensive areas of marsh habitat where plant species are adapted to a narrow range of variation in sea level. In theory, no net loss of marsh area might take place if new marsh development occurs at the same rate as marsh loss from flooding (Kennedy, 1990). However, human development often interferes with this process.

Based on all the available evidence from experiments, observations, and computer models, a change in climate of the magnitude projected by climate models is expected to have significant effects on the distribution and functioning of natural ecosystems of California, and on the services they provide. This general prediction can be made with confidence because, as already noted, climate is so important in determining the properties of ecosystems. It follows, then, that a change in climate must necessarily result in altered distributions and functioning.

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